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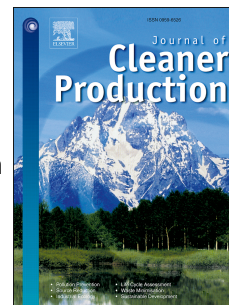
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Towards 100 % recycling of reclaimed asphalt in road surface courses: binder design methodology and case studies

Davide Lo Presti, Ana Jiménez del Barco Carrión, Gordon Airey, Elie Hajj



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1 **Towards 100 % recycling of reclaimed asphalt in road surface courses: binder design**
2 **methodology and case studies**

3 Lo Presti, Davide¹; Jiménez del Barco Carrión, Ana¹; Airey, Gordon¹; Hajj, Elie²

4 ¹Nottingham Transportation Engineering Centre, Pavement Research Building, University of
5 Nottingham, NG7 2RD, Nottingham UK - +44(0)11584 67993

6 ²University of Nevada, Reno, Nevada USA

7 Corresponding author: Davide Lo Presti – davide.lopresti@nottingham.ac.uk

8

9 **Abstract**

10 Reclaimed Asphalt (RA) has shown great potential to be reused in new asphalt mixtures, however its
11 incorporation in top asphalt pavement layers is still very limited (10-30%). In fact, despite the
12 advantages that its use implies, RA content in road pavement surface courses is still restricted in most
13 countries due to mainly legislation limitations, but also some technical issues. This paper aims at being a
14 step further to improve the latter by providing a methodology that allows producing fundamental inputs
15 for confidently performing mix design of asphalt mixtures incorporating up to 100% RA. The
16 methodology consists in an advanced preliminary binder's blend design that can be used with any type
17 of RA and also in presence of rejuvenators. This procedure includes in the production of blending charts
18 and laws that considers the uncertainties on accounting the extent of final binder content, Degree of
19 Blending and Replaced Virgin Binder. The description of the methodology is accompanied with results of
20 two extreme case studies consisting in the preliminary design of binders for asphalt mixtures with high
21 content of two types of RA corresponding to extreme cases: the short-term aged RA (STA-RA), having a
22 very soft residual binder (Pen > 20dmm) and the long-term aged RA, having a much harder residual
23 binder (Pen < 10dmm). As a result, the proposed methodology allowed assessing the feasibility of using
24 up to 90% of RA and determining whether the use of rejuvenating agents was needed.

25 **Keywords:** Reclaimed Asphalt, Rejuvenator, Binder design, Blending chart, Replaced Virgin Binder,
26 Recycling

27 1. Introduction

28 Current concerns about the scarcity of raw materials for the construction and maintenance of
29 roads (and the increase in price that it implies), together with the great potential shown by
30 Reclaimed Asphalt (RA) to be successfully recycled in asphalt mixtures, are encouraging the
31 increase of the use of this material to produce high RA content mixtures (Stimili et al. 2016).
32 For this purpose, great efforts are being made to understand how to recycle RA directly within
33 surface courses so to avoid its downgrading (Re-Road.fehrl.org, 2013). However, in general,
34 the share of recycling of RA in new asphalt courses remains rather lower than it could be
35 technically, being wearing courses the most challenging ones due to the required high
36 performance such as resisting distresses and skid resistance (West et al. 2016). In fact, despite
37 the advantages that its use implies, RA content in road pavement surface courses is still
38 restricted in most countries due to mainly legislation limitations, but also technical issues such
39 as: variability of RA properties, the often-unknown nature, uncertainties on mixture's
40 performance and the lack of fundamental understanding of some of the mechanisms involved
41 during its mixing with other components of asphalt mixes.

42 Generally, high RA content mixtures for wearing courses are considered those that have more
43 than 20-30% in weight, depending on the countries and type of RA (Austroads 2015). Different
44 studies have been carried out to shed lights on whether the increase of RA percentages in
45 wearing courses is actually feasible or not. (Sabouri et al, 2015a; Sabouri et al, 2015b; Doyle
46 and Howard 2010; Maupin et al. 2008). Beginning with low increases, Maupin et al. (2008)
47 reported the results of testing plant-produced mixes for wearing courses including 21-30% of
48 RA. They showed that there were no significant differences between the higher RA mixes and
49 the control mixes for fatigue, rutting and susceptibility to moisture. Binder testing showed that
50 the addition of RA raised the high temperature grading one to two grades, which should be
51 assumed in mix design, and care has to be taken at low temperatures. In addition, there were

52 no construction problems attributed to the use of the mix with higher RA percentages. The
53 same mixes were later studied by Apeageyi et al. (2013) to check the influence of the high RA
54 content in mix stiffness, finding that 30% RA did not produce a considerable effect on it.

55 Several studies showed that the key to increase the amount of RA in asphalt is a balanced mix
56 design (Canon Falla et al. 2016, Bueche et al. 2016). On this regard, Zhou et al. (2011)
57 developed a balanced RA mix design for high RA content mixtures for surface layers based on
58 changing the binder content of the mix to optimise the maximum density. To validate the
59 design, Zhou et al. (2011) built two field sections with 35% RA content mixes designed with
60 their methodology in different locations. The overall conclusion from the study was that
61 high RA mixes can have better or similar performance to virgin mixes, but they must be
62 well designed following appropriate mix design methods.

63 Going further in the increase of RA content, Doyle and Howard (2010) studied mixes for
64 wearing courses including 25 and 50% and considering the use of additives to produce warm
65 technologies. Durability, cracking and rut resistance and moisture damage of the mixes were
66 examined and results indicated that the use of high RA in surface mixtures would be feasible
67 without adversely affecting mix performance. Celauro et al. (2010) conducted another
68 investigation of mixtures with 50% RA content for surface layers concluding that, undertaking
69 a tailored design with such a high percentage of RA, mixtures with “high-performance” could
70 be obtained.

71 NCHRP Report 752 (West et al. 2013) showed that in mixtures with 55% RA content, stiffness
72 could increase up to 25-60% compared to virgin ones, thus leading to cracking problems. On
73 the other hand, rutting and moisture resistance are likely to be better or similar to those of
74 conventional mixtures as the percentage of RA increases (McDaniel et al. 2002; Silva et al.
75 2012; Tran et al. 2012; Mogawer et al. 2012).

76 Results of the Austroads report (2015), as well as Sabouri et al. (2015a; 2015b) reinforce the
77 previously published general trends that an increase in RA content leads to an increase in
78 stiffness of the asphalt, a reduction in fatigue life, and an increase in permanent deformation
79 resistance. The results do not suggest the RA content has an appreciable impact on moisture
80 sensitivity of the asphalt specimen. Furthermore, It was observed that for mixes with hard RA,
81 here called “long-term aged”, incorporating content below 30%, the performance properties
82 are very similar, but differ significantly from mixes with 60% of RA and those containing only
83 virgin binder (0% RA) (Austroads, 2015). Instead, when RA mixtures were manufactured with
84 even 40% of soft RA, here called “short-term aged”, results of performance-related tests
85 provided evidence of a little impact of the RA. This is justified from the little differences
86 between RA and virgin materials stiffnesses (Sabouri et al, 2015a; Sabouri et al, 2015b).

87 In summary, these studies all agree that obtaining good performance of high RA content
88 asphalt concretes strongly depends on RA properties and mixture design. Special attention has
89 to be paid to the mixture design due to the presence of the aged stiff binder. In fact the aged
90 binder could represent an advantage in terms of rut resistance at high service temperature (30
91 – 60C) but it usually favours cracking phenomenon at lower temperatures (+30C to below 0C).
92 Furthermore, these studies considered 50-60% RA content as almost a limit for asphalt mixes,
93 especially for surface courses. This is partially related to the final performance of the asphalt
94 concrete that will strongly depend on the properties of the RA, on the RA handling procedures
95 (Bressi et al., 2016) and also to the final grading curve of the targeted mixture that usually
96 needs fixing with additional virgin aggregates. Nevertheless, regardless of the final
97 performance of the asphalt, so far the main technical reason playing against 100% RA asphalt
98 mixtures has been technological and it is due to limitations of the majority of existing asphalt
99 plants that, due to equipment design issues (such as fumes produced by over-heated RA), are
100 not able to incorporate more than 50-60% in new asphalt mixtures (Zaumanis & Mallick,
101 2015). Current aspirations are to achieve greater RA rates (aiming at 100%) in order to

102 maximise the advantages of RA usage, however technological change of the asphalt plants is
103 needed and it's sporadically happening (Rowe et al., 2015; Zaumanis et al., 2014)), but also
104 material characterisation and binder and mixtures design should be adapted to consider RA as
105 the main ingredient, while ensuring the usual desired performance (Canon Falla et al., 2015; Lo
106 Presti et al. 2014).

107 In this regard, investigating technologies and procedures to take advantage of the binder
108 already contained in the Reclaimed Asphalt binders (RA binders) play a critical role (Hassan et
109 al. 2015, Zaumanis et al. 2014; Zhao et al. 2016). Therefore, developing a proper binder blend's
110 design between RA binders and virgin materials is the first step for designing feasible 100% RA
111 content mixtures. Currently, different approaches are being followed to carry out this task in
112 different countries. In Europe, the standard EN 13108-8:2005 for reclaimed asphalt establishes
113 that if RA content is higher than 10% for surface layers and than 20% for base layers, a
114 logarithmic blending law for penetration and a linear blending law for softening point should
115 be applied to select the proper virgin binder to use. On the other hand, in the United States of
116 America, for high RA contents (>20%), NCHRP Report 452 (2001) described a particular
117 procedure to obtain blending charts assessing high, intermediate and low critical temperatures
118 of the blend of RA and virgin binder. After building blending charts, next step in both
119 specifications is to use the final RA percentage in the mix to obtain the value that the property
120 under assessment (i.e. penetration, softening point, etc.) would have after the manufacture of
121 the mixture. Nevertheless, RA percentage is not the percentage of RA binder that will be
122 blended with the virgin binder. The real percentage of RA binder that will blend is known as
123 Replaced Virgin Binder (RVB) and depends on several factors such as RA binder content, binder
124 content in the final mixture and the degree of blending (DOB) between virgin and aged
125 binders. NCHRP Report 752 (West et al. 2013) already suggested using what they called "RAP
126 binder ratio" but only taking into account binder content in the mixture. Regarding the DOB,

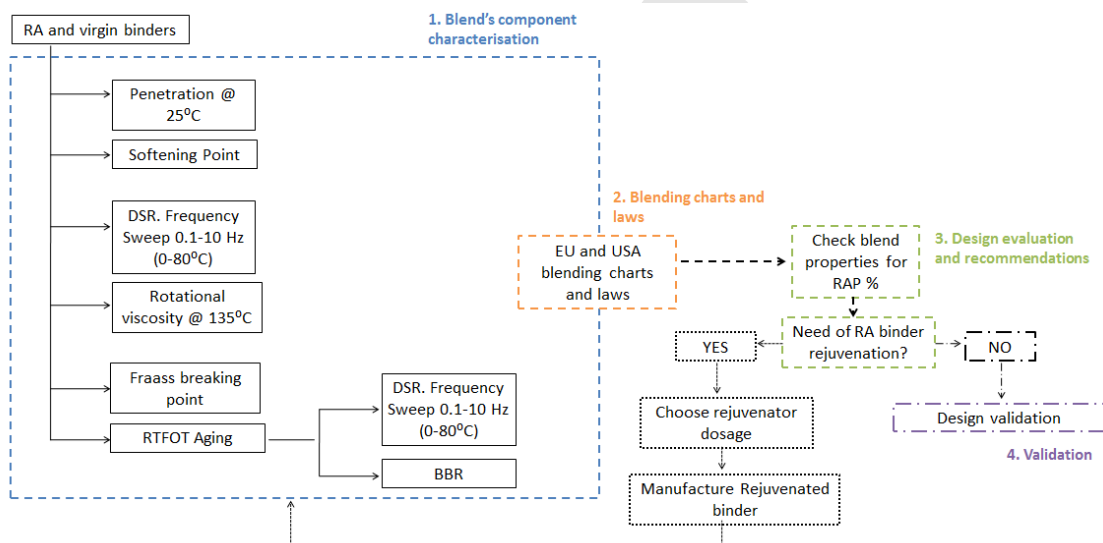
127 recent researches have argued that for high RA contents (>20%) high blending rates take place
128 (Soleymani et al., 2000; Shirodkar et al. 2011; McDaniel et al. 2012).

129 Other aspect to take into account while developing blend design is that when RA content is
130 wanted to be higher than a certain percentage (limitations depends on RA properties and local
131 specifications), or when RA contains particularly hard aged binder, it could be necessary to
132 introduce another component in the mix (in addition to the virgin binder). This component is
133 commonly known as rejuvenator or rejuvenating/recycling agent and is responsible for
134 restoring some of the properties that the reclaimed material had before its service life (Shen
135 and Ohen, 2002; Karlsson and Isacsson 2006; Romera et al. 2006; Tran et al. 2012). The effect
136 of rejuvenators on RA mixes has already been studied and applied in full-scale by some
137 authors (Mallick et al. 2010; Silva et al. 2012; Zaumanis et al. 2013) showing that these
138 materials could allow the use of 100% RA mixes for wearing courses. However, traditional
139 binder blend's design still only considers RA and virgin binders without taking into account the
140 use of rejuvenators.

141 Within this framework, this paper proposes a methodology that allows predicting the binder's
142 properties of the asphalt mixtures containing up to 100% RA. This methodology consists in the
143 construction of blending charts for conventional and performance-related binder properties,
144 including the use of RVB and DOB concepts, it allows including the use of rejuvenators and it is
145 independent of the RA source. In order to prove the flexibility of the methodology with
146 regards to the RA source, this investigation shows also the results of the application of this
147 methodology with two case studies corresponding to extreme conditions of RA sources: the
148 short-term aged RA (STA-RA), having a very soft residual binder (Pen > 20dmm) and the long-
149 term aged RA, having a much harder residual binder (Pen < 10dmm). Results are presented and
150 discussed together with recommendations for an immediate implementation from
151 contractors, researchers, asphalt professionals and road engineers.

152 2. Preliminary Binder's design methodology

153 Most countries have developed their own blending models for the use of RA binder and
 154 rejuvenators in new asphalt mixtures. Thereby, European countries use conventional
 155 properties to design blends, while USA use performance-related properties. The proposed
 156 methodology includes a combination of the two (Figure 1). In this study, only the results of the
 157 binder design for both case studies are shown. More details on each of the undertaken step
 158 are published elsewhere (Jiménez del Barco Carrion et al. 2015). Furthermore, the procedure
 159 will include the flexibility of using rejuvenators, as well as the other key concepts: RVB and
 160 DOB concepts. Final procedure and testing plan followed by the authors are summarized in
 161 Figure 1.



162

163

Figure 1. Preliminary binder design methodology for high-content RA asphalt mixture

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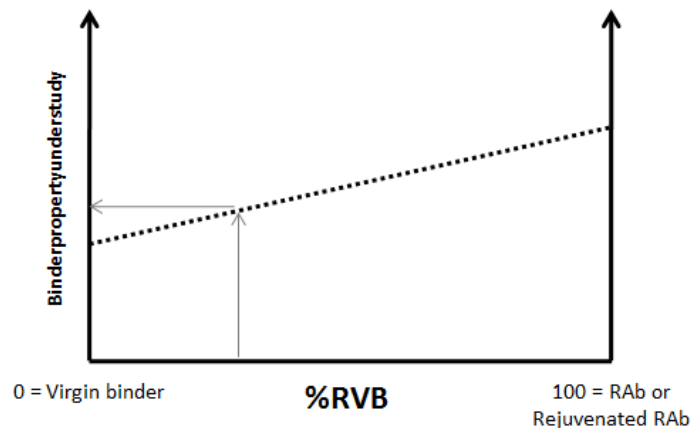
165 As depicted in Figure 1, the proposed methodology includes four stages as follows:

166 1. Blend's component characterisation (in blue in Figure 1)

167 In this step, RA and virgin binders are tested to be conventionally and rheologically
 168 characterised according to the plan showed in Figure 1

169 2. Building blending charts and laws (in orange in Figure 1)

170 Once each of the final blend component have been characterised, blending charts are built on
 171 the basis of the selected blending laws between RAb and usually fresh bitumen. Blending laws
 172 are the models internationally used to assess the property of the final blend depending on the
 173 dosage of each component (EN 13108-8:2005; NCHRP Report 452 2001). 'Blending charts' are
 174 graphs in which the x-axis usually represents the percentage of RA in the asphalt mix from 0%
 175 to 100%, while the y-axis represents the property of the binder that we want to target in the
 176 design procedure (i.e. Pen). In this sense, the 0% RA represents the value of the property of
 177 the rejuvenator (i.e. neat bitumen) and the 100% is usually the property of the RA binder that
 178 will be blended with the virgin binder.



179

180

Figure 2. Example of proposed blending chart

181

182 Figure 2 shows the blending chart of the proposed methodology which is based on a linear
 183 blending law and that includes the possibility of incorporating rejuvenating agent for the RA.
 184 For this reason the x-axis represent the Replaced Virgin Binder (RVB), while the 100% y-axis
 185 represent the properties of Rejuvenated RAb. Using the RVB% in place of the RA% is a key fact
 186 affecting also the blending laws where RA percentages are not the in weight in the mix but the
 187 real percentage of virgin binder that will be replaced by RA. As mentioned earlier, this value is

188 called the Replaced Virgin Binder (RVB) and is calculated following Equation 1 with all the
189 parameters expressed in decimals.

$$190 \quad RVB (\%) = 100 \cdot \frac{RA \text{ content in the mixture} \cdot DOB \cdot RA \text{ binder content}}{\text{binder content in the mixture}} \quad (1)$$

191

192 Where,

- 193 • *RA content in the mixture*: is the total RA percentage to add in the mixture by weight,
- 194 • *RA binder content*: is the binder content in the RA
- 195 • *binder content in the mixture*: is the designed final binder content in the mixture,
196 which is considered having Variability of the final binder content in the mixture (\pm
197 0.5%)
- 198 • *DOB*: is the assumed degree of blending between RA and virgin binders. In fact, given
199 that the real percentage of blending that will occur on the mix is unknown, the
200 possibility of 100 and 60% of blending was considered. This initial hypothesis was
201 based on previous research of other authors who found that for high RA percentages
202 high blending is achieved (Soleymani et al. 2000; Shirodkar et al. 2011; McDaniel et al.
203 2012). These authors experimentally obtained the DOB through different procedures
204 such as comparing the performance of mixes with different RAP content (Soleymani et
205 al. 2000), manufacturing mixes only with fine RAP and virgin coarse aggregates and
206 observing the effect (Shirodkar et al. 2011) or using Hirsch model to predict full
207 blending and then comparing with experimental results (McDaniel et al. 2012).

208

209

210

211

212 3. Design evaluation and Recommendations (in green in Figure 1)

213 Having the blending charts, the desired RA percentages are replaced in them and the value of
214 each property of the final binder blend is predicted and compared to the target. In the case
215 studies shown in this paper, the two fresh binders represented the target. From this
216 comparison, then it will be possible to predict whether incorporating the selected RA% will
217 provide an asphalt mixture with acceptable properties, or if rejuvenating agents are needed,
218 only depending on the binder properties. This final recipe will provide confirmation on the
219 quantity and quality of the chosen blend components and will represents the desired inputs
220 for a further mix design.

221 4. Design validation (in purple in Figure 1)

222 Once an acceptable binder recipe is found, with or without rejuvenators, validation is
223 performed by means of blending the binders in the laboratory in the previously determined
224 proportions and subjecting them to further testing that will be compared with binder
225 recovered from the resulting high-content RA mixture. The results of this comparison will
226 provide information on the accuracy of the preliminary design and potentially also the actual
227 occurred DOB.

228

229 **3. Case Studies: binder design with Short (RA-STA) and Long Term Aged RA (RA-LTA)**

230 RA coming from two different sources were specifically selected and identified as: short term
231 aged RA (RA-STA) and long term aged RA (RA-LTA). It was known that RA-STA was
232 manufactured with a polymer modified binder denominated as PMB 25/55-25, meaning that
233 its needle penetration at 25°C is within the range 25-55 dmm (according to EN 1426:2007) and
234 its ring & ball softening point is equal or higher than 55°C (according to EN 1427:2007). On the
235 other hand, RA-LTA was manufactured with a conventional 50/70 penetration grade bitumen
236 (penetration within the range 50-70 and softening point within the range 46-54°C according to

237 EN 12591:2009). In order to characterise both RAs, binder contents were determined following
 238 the standard EN 12697-1:2012. At last, binders were recovered from the RA following EN
 239 12697-4:2005.

240 The virgin bituminous binders to be added to RA to achieve the desired targeted properties of
 241 the final asphalt mixtures were selected to be the same than the one used in the manufacture
 242 of the RAs. These would be: a PMB 25/55-55 for the RA-STA mixtures the virgin binder and
 243 50/70 penetration grade for the asphalt mixes incorporating RA-LTA .

244 Furthermore, as detailed by the binder blend's design, for some of the mixes also a
 245 rejuvenator (Rej) was needed. This was selected to be a special combination of regenerated oil
 246 and a Fischer-Tropsch wax that is specifically produced to allow manufacturing asphalt
 247 concrete with very high content of RA. In fact, the oil rejuvenates the bitumen of the RA to a
 248 predetermined degree of softness, while the Fischer-Tropsch wax improves the mixability and
 249 workability of the asphalt.

250

251 **3.1. Blend's components characterisation**

252 Table 1 shows the results of the conventional tests undertaken for RAb-STA, RAb-LTA and
 253 virgin binders (VB-STA and VB-LTA). It can be observed the effect of ageing over RA binders:
 254 penetration decreases due to hardening while softening point, rotational viscosity and Fraass
 255 breaking point increase.

256

Table 1. RAb and VB conventional properties

BITUMEN	Penetration @25°C (dmm)	Softening point (°C)	Rotational viscosity @ 135°C (mPa.s)	Fraass breaking point (°C)
RAb-STA	21.7	65.7	1518	-8
VB-STA	43	60.4	1195	-16
RAb-LTA	8.3	71.4	1827	+8.7
VB-LTA	68	47.6	273	-8

257 High, intermediate and low critical temperatures for both binders are shown in Table 2. BBR
 258 temperatures were selected based on previous DSR results. Critical temperatures in Table 2
 259 are the final evidence of the effect of ageing in the binder. High and intermediate
 260 temperatures slightly increased for the short term aged RA case and in a more notable way for
 261 the long term aged RA case. In this sense, RA binders exhibit better resistance to rutting and
 262 fatigue. On the other hand, the increase of low critical temperature (i.e. warmer low
 263 temperature) in both cases would worsen thermal cracking behaviour. Differences between
 264 RAb-STA and VB-STA are not very significant, which confirms that RA-STA is a 'young' RA. On
 265 the contrary, differences between RAb-LTA and VB-LTA are more visible, meaning that RAb-
 266 LTA is an 'old' RAb.

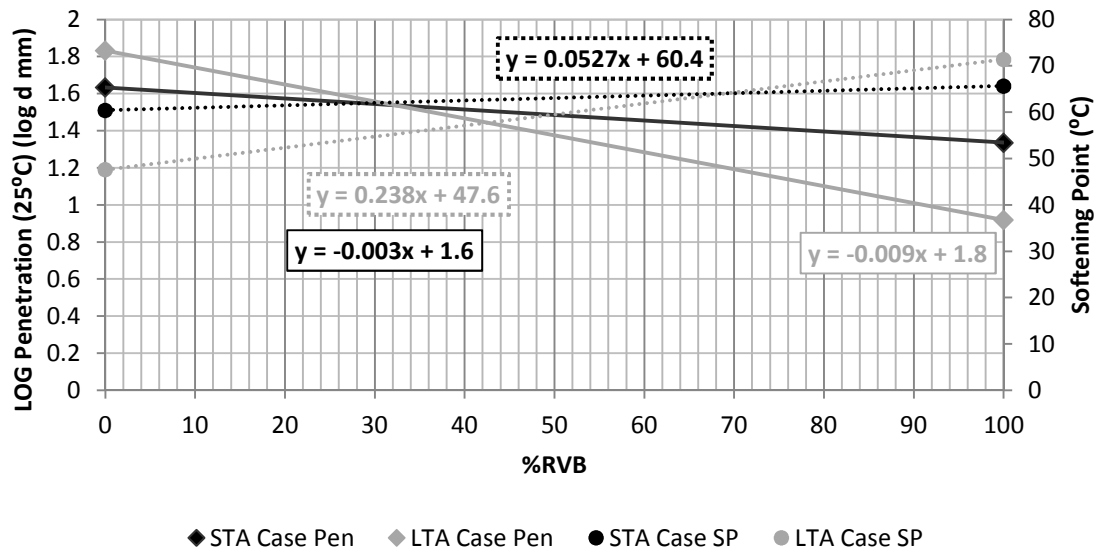
267 **Table 2. Critical temperatures for RAb and VB**

Binder	High (°C)	Intermediate (°C)	Low (°C)
VB-STA	79.4	19.1	-16
RAb-STA	80.1	22.5	-13.5
VB-LTA	66	19	-16
RAb-LTA	87	33	-6

268

269 **3.2. Blending charts**

270 Once the testing was finished, blending charts and laws were constructed for penetration,
 271 softening point and critical temperatures. Those charts are shown in Figure 3 and Figure 4.



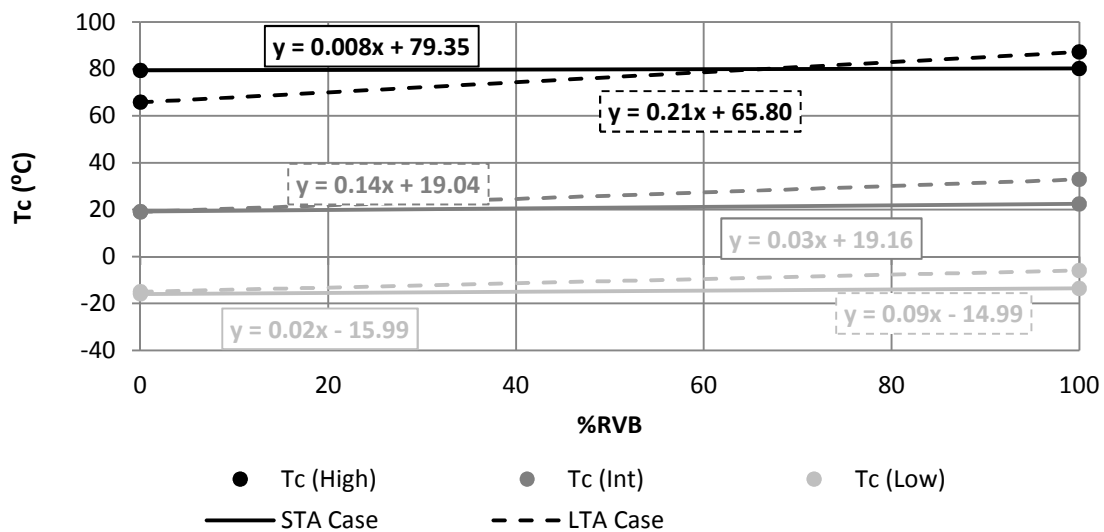
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Figure 3. Penetration at 25°C (Pen) and softening point (SP) blending chart and law between RA and virgin binders



276

277

278

Figure 4. Critical temperature blending chart and law between RA and virgin binders

279 In the short term ageing case study, the aim was to assess the possibility of manufacturing

280 mixtures with 30, 60 and 70% of RA-STA. The limitation to 70% was due to the differences

281 between the RA-STA and the final grading curve of the targeted mixes. In other words, for

282 issues related with the aggregate skeleton, it is not possible to manufacture the targeted

283 asphalt mixes with 100% of the selected RA-STA. The binder content in the RA-STA was found

284 to be 4.86% and final binder content in the mix was defined as 7.2%. Due to possible changes
 285 in the asphalt plant, to see the effect of the binder content in the mix and due to that different
 286 RA content changes the optimum binder content of the mix, a variability of $\pm 0.5\%$ was
 287 considered, so also 7.0 and 7.4% were considered.

288 On the other hand, in the long term aged RA case, 30, 60 and 90% of RA-LTA in weight of the
 289 mix were considered for the design. In this case, the selected RA-LTA was quite “compatible”
 290 with the targeted asphalt mixture, to the point that based on grading curves it is possible to
 291 recycle up to even 90% of the RA-LTA. The binder content of this RA was obtained for the fine
 292 and coarse fraction as 6.83% and 4.76% respectively, being each fraction 52.16 and 47.84% of
 293 the total RA-LTA. Binder content in the long-term aged RA mixtures would be 6.5% but also 6.0
 294 and 7.0 % were considered in the calculations. Given these parameters, RVB percentages were
 295 calculated and are shown in Table 3 and Table 4 for each case. As explained above, in both
 296 cases the maximum amount of RA% was established, elsewhere, by checking how close the RA
 297 grading curves were from the targeted grading bands of the selected mixtures.

298

299 **Table 3. Replaced Virgin Binder (RVB) percentages and blend results for the short term aged RA case study**

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB	PEN (dmm)	SP (°C)	High Critical temp.	Int Critical temp.	Low Critical temp.
	0		0	43	60.4	79.4	19.1	-16
100%	30	6.7	21.76	37.0	61.5	79.5	19.9	-15.5
		7.2	20.25	37.4	61.5	79.5	19.8	-15.5
		7.7	18.93	37.8	61.4	79.5	19.8	-15.5

60%	30	6.7	13.06	39.3	61.1	79.5	19.6	-15.7
		7.2	12.15	39.6	61.0	79.5	19.6	-15.7
		7.7	11.36	39.8	61.0	79.4	19.5	-15.7
100%	60	6.7	43.53	31.9	62.7	79.7	20.6	-14.9
		7.2	40.50	32.6	62.5	79.7	20.5	-15.0
		7.7	37.87	33.2	62.4	79.7	20.4	-15.1
60%	60	6.7	26.11	36.0	61.8	79.6	20.0	-15.3
		7.2	24.30	36.4	61.7	79.5	20.0	-15.4
		7.7	22.72	36.8	61.6	79.5	19.9	-15.4
100%	70	6.7	50.78	30.4	63.1	79.8	20.8	-14.7
		7.2	47.25	31.1	62.9	79.7	20.7	-14.8
		7.7	44.18	31.8	62.7	79.7	20.6	-14.9
60%	70	6.7	30.47	34.9	62.0	79.6	20.2	-15.2
		7.2	28.35	35.4	61.9	79.6	20.1	-15.3
		7.7	26.22	35.9	61.8	79.6	20.0	-15.3
	100		100	21.7	65.7	80.1	22.5	-13.5

300

301

302

Table 4. Replaced Virgin Binder (RVB) percentages and blend results for the long term aged RA case study

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB	PEN (dmm)	SP (°C)	High Critical temp.	Int Critical temp.	Low Critical temp.
	0		0	68	47.6	66	19	-16
100%	30	6.0	29.20	36.8	54.5	72.1	23.1	-12.3
		6.5	26.95	38.6	54.0	71.6	22.8	-12.6
		7.0	25.03	40.2	53.6	71.2	22.5	-12.7
60%	30	6.0	17.52	47.0	51.8	69.6	21.5	-13.4
		6.5	16.17	48.4	51.4	69.3	21.3	-13.5
		7.0	15.02	49.6	51.2	69.0	21.1	-13.6
100%	60	6.0	58.40	19.9	61.5	78.3	27.1	-9.7
		6.5	53.91	21.9	60.4	77.4	26.5	-10.1
		7.0	50.05	23.7	59.5	76.5	26.0	-10.5
60%	60	6.0	35.04	32.5	55.9	73.3	23.9	-11.8
		6.5	32.37	34.4	55.3	72.7	23.5	-12.1
		7.0	30.03	36.2	54.7	72.2	23.2	-12.3
100%	90	6.0	87.60	10.8	68.4	84.6	31.2	-7.1
		6.5	80.86	12.4	66.8	83.1	30.2	-7.7
		7.0	75.08	14.0	65.5	81.9	29.4	-8.2
60%	90	6.0	52.56	22.5	60.1	77.1	26.3	-10.2
		6.5	48.51	24.5	59.1	76.2	25.8	-10.6
		7.0	45.05	26.4	58.3	75.5	25.3	-10.9

100	100	8.3	71.4	87	33	-6
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303

304 Having the blending laws and the RVB percentages, the theoretical values of the evaluated
305 properties of the blend between RAb and VB at the desired percentages were obtained. These
306 results are shown in Table 3 and Table 4. Table 3 and Table 4 also include the values of
307 hypothetical 0% and 100% RA as a reference to see how property values change approaching
308 each extreme.

309 At this point, both cases have to be independently analysed through answering the question:
310 do we need a rejuvenator for using those RA binders blended with the virgin binders and
311 achieve the target? Therefore, from now on both cases are independently presented.

312

313 **3.3. Design evaluation and Recommendations**

314 **3.3.1. Short term aged RA case study (soft RA)**

315 Short term aged RA target binder to achieve with the blend of RAb-STA and VB-STA is a PMB
316 55-25/55 (same than VB-STA). In this sense, if results from Table 3 are compared with the
317 target binder:

- 318 • Penetration values are within the range 30.4 - 39.8 dmm for every RA percentage and
319 blending assumption, and therefore within the limits of a PMB 55-25/55.
- 320 • Softening point is always higher or equal to 61°C, thus is higher than 55°C.
- 321 • High critical temperature is always higher than the VB-G ones, which could imply a
322 better rutting resistance.
- 323 • Low and intermediate critical temperatures are higher than the VB-STA one, but being
324 maximum 1.2°C higher in the case of the low temperature, and 1.7°C in the case of the

325 intermediate temperature, always for the assumption of 100% blending and 70% of
326 RA.

327 Given these claims, the final recommendations for the mix design with RA-STA are: there is no
328 need of rejuvenator in any of the RA and blending percentages considered. However, some
329 issues could arise with low temperature cracking phenomenons.

330 **3.3.2. Long term aged RA case study (hard RA)**

331 Target binder for the RA-LTA mixtures was a 50/70 penetration grade bitumen (same than VB-
332 LTA). Comparing the results of the blend design between RAb-LTA and VB-LTA from Table 4
333 and the target binder, it can be said that:

- 334 • Penetration values are not within the range 50-70 dmm in any of the RA-LTA
335 percentages or blending assumptions considered but lower.
- 336 • Blend softening point is higher than 54°C for all the RA-LTA and blending percentages
337 considered. In this sense, none of the blends can be considered a 50/70 penetration
338 grade bitumen.
- 339 • High critical temperature of the blends is higher than VB-LTA one which could be seen
340 as an advantage.
- 341 • Low and intermediate critical temperatures of the blends are higher than the VB-IT
342 ones which could lead to a lower fatigue and thermal cracking resistance.

343 Due to the RAb-LTA characteristics, the blend with the VB-LTA is not able to achieve an
344 adequate binder to be used in high RA content mixtures. Therefore, a new blend design
345 considering the use of the rejuvenator was carried out.

346

347 Blend design with rejuvenator: The first step in carrying out the blend design with a
 348 rejuvenator was to define the ratio between the rejuvenator and the RAb-LTA to obtain the
 349 Rejuvenated RAb- LA. In this case, this additive/RAb-LTA ratio was selected following the
 350 instructions of the provider of the additive: $Rej/RAb-LTA = 0.2$. This dosage recommendation
 351 was based on empirical experiences of the provider. Due to the introduction of a new
 352 component in the mixture, RVB (%) have to be calculated again taking into account each
 353 rejuvenator ratio following Equation (2):

$$354 \quad RVB (\%) = 100 \cdot \frac{RA \text{ in the mixture} \cdot DOB \cdot RAb \text{ content} \cdot (1+REJ \text{ ratio})}{binder \text{ content in the mixture}} \quad (2)$$

355 Where, RA in the mixture is the total RA percentage to add in the mixture by weight, DOB is
 356 the assumed degree of blending between RA and virgin binders, RAb content is the binder
 357 content in the RA, REJ ratio is the ratio Rej/RAb for each rejuvenator and binder content in the
 358 mixture is the designed final binder content in the mixture, being all the parameters expressed
 359 in decimals.

360 In this sense, %RVB were calculated for the different combinations (18 in total). These values,
 361 shown in Table 5, will then be replaced in the blending laws to obtain the property of the final
 362 blends. From Table 5, it can be observed that when the percentage of RA is 90%, full blending
 363 is considered (100%) and binder content in the mix is 6%, the RVB percentage is higher than
 364 100%. This result leads to assess that when full blending is considered (100%), 6% binder
 365 content for the 90% RA mixture is not enough to achieve the desired rejuvenation effect for
 366 the selected RA. Therefore, if the mix design will identify 6% as the optimum binder content,
 367 other Rejuvenators with higher rejuvenating effect (lower amount) would need to be selected.
 368 However, increasing the binder content to 6.5%, or assuming that partial blending would take
 369 place, RVB percentages are again less than 100% and the mix manufacture would be feasible
 370 with the selected rejuvenator.

371

Table 5. Percentages of Replaced Virgin Binder (%RVB) for the blend design with rejuvenator

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB
100%	30	6.0	34.8
		6.5	32.1
		7.0	29.8
60%	30	6.0	20.9
		6.5	19.3
		7.0	17.9
100%	60	6.0	69.6
		6.5	64.2
		7.0	59.7
60%	60	6.0	41.8
		6.5	38.5
		7.0	35.8
100%	90	6.0	104.4
		6.5	96.4
		7.0	89.5
60%	90	6.0	62.6
		6.5	57.8
		7.0	53.7

372

373 Table 6 shows the results of the conventional characterisation of Rejuvenated RAb-LTA. From
374 the results, the softening effect that both rejuvenators exert in the RAb-LTA can be seen as
375 compared to the RAb-LTA initial properties showed in Table 1. The rejuvenator increased the
376 penetration of the RAb-LTA. It has to be said that the penetration value of the Rejuvenated
377 RAb-LTA is not completely reliable due to the nature of the additive, which after one hour in a
378 test conditioning bath at 25°C showed signs of phase separation. However, it was taken as an
379 approximation for the design. Softening point of the Rejuvenated RAb-LTA with rejuvenator
380 decreased 3⁰C. It is also worth noting the remarkable reduction that the rejuvenator produced
381 in the viscosity of the RAb-LTA at 135°C, which would significantly enhance the workability of
382 the bituminous mixture (due to the waxes).

383

384

385

Table 6. Conventional properties of Rejuvenated RAb-LTA

Binder	Additive/RAb-IT Ratio	Penetration @ 25°C (dmm)	Softening point (°C)	Rotational viscosity @ 135°C (mPa.s)
Rejuvenated RAb-LTA	0.2	92	68.4	372.5

386

387 Critical temperatures of the rejuvenated binder were obtained according to NCHRP Report 452
 388 (2001). Table 7 displays these results. They highlight the effect of the rejuvenator in the RAb-
 389 LTA, which decreases the intermediate and low critical temperatures (i.e. colder critical
 390 temperatures) and maintains the high critical temperature. This effect implies that the
 391 rejuvenator improve fatigue and thermal cracking resistance without affecting plastic
 392 deformation resistance. These results are in accordance with those showed by others authors
 393 (Tran et al. 2012).

394

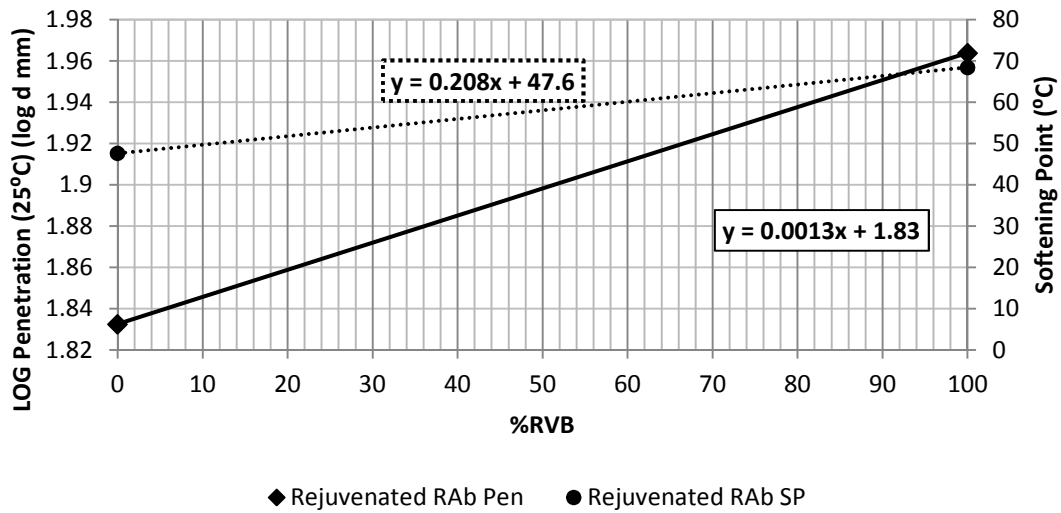
Table 7. Critical temperatures for Rejuvenated RAb-LTA

Binder	High (°C)	Intermediate (°C)	Low (°C)
Rejuvenated RAb-LTA	71	11	-21

395

396 Blending charts and blending laws for the blend of Rejuvenated RAb-LTA with VB-LTA are
 397 shown in Figure 5 and Figure 6. Table 8 displays the result of using the blending laws with the
 398 %RVB from Table 5, which takes into account all the design parameters.

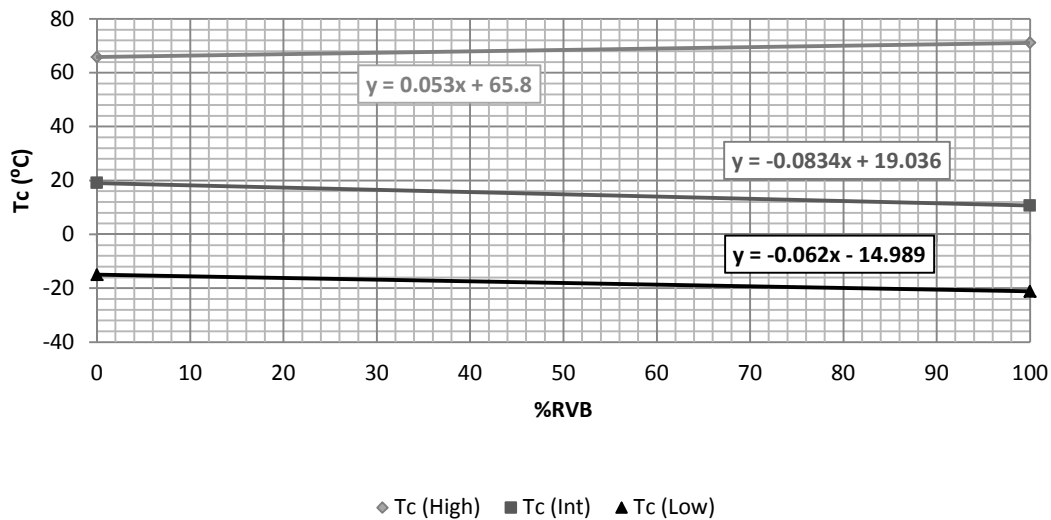
399 According to Table 8, final blends of Rejuvenated RAb-LTA and VB-LTA would be feasible for
 400 mixture production with every RA percentage, even 90%. Although penetration results seem a
 401 bit high, the rest of the studied properties show convenient binders for the manufacture of
 402 high RA content mixtures. This fact could be due to the nature of procedure used for
 403 penetration tests and the phase separation signs already commented. Critical temperatures
 404 reveal good binder performance in comparison to resist rutting. However, some attention
 405 should still be taken in terms of fatigue and thermal cracking.



406

407
408

Figure 5. Penetration at 25°C (Pen) and softening point (SP) blending chart and law between Rejuvenated RAb-LTA and VB-LTA



409

410

Figure 6. Critical temperature blending chart and law between Rejuvenated RAb-LTA and VB-LTA

411

412

Table 8. Replaced Virgin Binder (RVB) percentages and blend results for the long term aged RA case study with rejuvenators

Estimated Degree of Blending (DOB)	%RA	% Binder	% RVB	Pen 25°C dmm	SP (°C)	Tc High	Tc Int	Tc Low
100%	30%	6.0	34.8	75.5	54.8	67.6	16.1	-17.1
		6.5	32.1	74.9	54.3	67.5	16.4	-17.0
		7.0	29.8	74.4	53.8	67.4	16.6	-16.8
60%	30%	6.0	20.9	72.4	51.9	66.9	17.3	-16.3
		6.5	19.3	72.1	51.6	66.8	17.4	-16.2
		7.0	17.9	71.8	51.3	66.7	17.5	-16.1

100%	60%	6.0	69.6	83.9	62.1	69.5	13.2	-19.3
		6.5	64.2	82.6	61.0	69.2	13.7	-19.0
		7.0	59.7	81.4	60.0	69.0	14.1	-18.7
60%	60%	6.0	41.8	77.1	56.3	68.0	15.6	-17.6
		6.5	38.5	76.4	55.6	67.8	15.8	-17.4
		7.0	35.8	75.8	55.0	67.7	16.1	-17.2
100%	90%	6.0	104.4	-	-	-	-	-
		6.5	96.4	91.0	67.6	70.9	11.0	-21.0
		7.0	89.5	89.1	66.2	70.5	11.6	-20.5
60%	90%	6.0	62.6	82.2	60.6	69.1	13.8	-18.9
		6.5	57.8	81.0	59.6	68.9	14.2	-18.6
		7.0	53.7	80.0	58.8	68.6	14.6	-18.3

413

414 **4. Summary of results**

415 The proposed methodology was adopted with two extreme case studies aiming at providing
416 inputs for mix design of asphalt up to 90% of Short Term and Long Term aged RA. The
417 developed design includes the consideration of conventional and performance-related
418 properties of binders through the production of blending charts and laws. The concept of
419 Replaced Virgin Binder in the mixture was considered in the design, as well as the degree of
420 Blending between RA and virgin binders that was assumed being between 100 and 60%. This
421 design allowed predicting whether the chosen fresh binders, in combination with each of the
422 RAs, lead to obtain a binder blend with the desired target properties, or determining whether
423 the use of rejuvenators was needed.

424 In the short term aged RA case study, it was understood that the design could be performed
425 without the need of rejuvenators for the mixes with 30, 60 and 70% RA mixtures.

426 On the other hand, in the long term aged RA case study, results of the recovered RA binder
427 revealed that it was not possible to design a binder for the targeted asphalt mixtures, 30, 60
428 and 90% RA, without using rejuvenating oils. Thus, a new design was carried out considering
429 Rejuvenated RA and virgin binders. The new design showed improvements in final blend

430 behaviour and fundamental inputs to confidently manufacture well-performing asphalt
431 mixtures.

432 The main reason of the different approach used for the preliminary design with STA-RA and
433 LTA-RA, stands in the relative difference with the respective selected virgin binders (Table 2).
434 In fact, STA-RA binder has very similar rheological and conventional properties when
435 compared to the selected virgin binder, while the relative differences in the case of LTA-RA is
436 much more significant.

437 Other important findings:

- 438 - Degree of Blending and Replaced Virgin Binder concepts are extremely important in
439 order to carry out a realistic blend design. These concepts have great influence on
440 obtaining blend properties from blending charts and laws.
- 441 - Before undertaking binder design with virgin and Rejuvenated RA binders, a right
442 rejuvenator dosage has to be defined to obtain the desired rejuvenating effect on RA
443 binder. Then, Replaced Virgin Binder percentages have to be calculated taking into
444 account the percentage of RA into the mixture and the amount of rejuvenators. This
445 point is important to ensure that the mix design is feasible with the selected
446 rejuvenators' ratios.
- 447 - The two case studies have proved that every RA binder should be carefully studied
448 before being used in the selected asphalt mixtures. Depending on RA binder
449 properties, RA could be used in different ways, needing rejuvenating agents or not.
- 450 - Care has to be taken when testing RA binders with rejuvenator oils for needle
451 penetration since phase separation issues could occur, making results meaningless.
- 452 - The use of the rejuvenator has improved RA binder behaviour up to the point of
453 allowing the increase of RA content in the selected mixture up to 90%.

454 - Future work to improve the methodology should be focused on developing methods
455 to obtain rejuvenator dosages to restore RA binder properties.

456 -

457 **5. Discussion and Conclusions**

458 The take-away fact of this research is that in order to conceive asphalt mixtures mainly made
459 of RA (higher 50% RA), it is necessary to perform a detailed preliminary binder's blend design
460 that can provide fundamental inputs for the mix design phase. This investigation provide such
461 advanced methodology that allows tailoring binder blend's recipes to manufacture asphalt
462 mixtures incorporating up to 100% RA. This procedure is based on adapted blending charts and
463 laws allowing the use of rejuvenating agents and the possibility of varying the value of key
464 concepts such as final binder content, Degree of Blending (DOB) and Replaced Virgin Binder
465 (RVB). Authors are aware that in order to obtain such a drastic increase of RA in asphalt
466 mixtures, a technological change is needed for most of the existing asphalt plant and other
467 factors should play in favour such as local policies and improved RA handling to ensure that RA
468 gradation and quality are not a limitation. However, sporadically these changes are happening
469 already and considering that RA is the most recycled material in the planet, this trend is likely
470 to grow exponentially. With this in mind, this research offers a validated methodology that
471 can already be used from asphalt technologists to have better control when maximising the
472 amount of RA in ordinary asphalt plants (up to 50-60%) and can represent a fundamental tool
473 for those practitioners tailoring binder recipes in the few existing asphalt plant allowing
474 producing mixture with 100%RA.

475

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Paper title:

**TOWARDS 100 % RECYCLING OF RECLAIMED ASPHALT IN ROAD SURFACE COURSES:
BINDER DESIGN METHODOLOGY AND CASE STUDIES**

Highlights:

- Review of current practices, policies and limitations for using reclaimed asphalt (RA) in asphalt road surfaces
- Methodology to design binders for asphalt mixtures for road surfaces incorporating up to 100% RA
- Design, evaluation and recommendations for two case extreme studies differentiating for the type of RA source
- Adaptation of the design methodology with the use of rejuvenators